GCAS 2006/07 Project Report

Antarctic Dosimetry

A Preliminary Study of Background Radiation Levels at High Latitudes

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ABSTRACT

A significant proportion (13%) of the natural background radiation is of cosmic origin. Charged particles (e.g. from the Sun), such as protons, interact with the magnetic field of the Earth and can be deflected by it. This effect is reduced at the magnetic poles. Still, particles that enter the Earth's atmosphere commonly do not reach its surface, as they are slowed down by scattering and collisions. Therefore, most of their energy reaches the Earth's surface in the form secondary particles and photons (e.g. X-rays). As charged particles are less deflected at the magnetic poles, an increase of ionising radiation dose similar to what has been reported in aircrew, is expected at high (magnetic) latitudes. Similarly, it is well known that UV radiation levels are raised in Antarctica, where the atmosphere has been compromised. Measurements of UV and X-ray radiation levels were conducted in Antarctica in December and January 2006/2007, in order to investigate the relative intensities of both ionising and non-ionising radiation in the South Polar Region compared to Christchurch, New Zealand. While increased levels of UVA and UVB radiation were measured, the TLD dosimeters used for X-ray measurements were found to be too insensitive to significantly detect changes in radiation levels.

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1. INTRODUCTION

"My main frustration is the fear of cancer from low dose radiation, even by radiologists." – The implications of this statement by one of the founding fathers of medical physics, John R. Cameron, have been one cause for controversy for many years. The effects of "low levels" of radiation are still far from being fully understood and while connections between increased background radiation and cancer occurrence have been observed in some locations, there is evidence for the reverse in others (Cameron, 1998). Background radiation is the radiation that any individual is exposed to naturally anywhere on Earth. It is commonly divided into cosmic-, terrestrial- and internal radiation, according to the location of its source. Cosmic radiation accounts for approximately 13% of the total background (Anchordoqui, 2002). It originates from the Sun and other stars and can be in the form of heavy particles (e.g. protons) or photons (e.g. X-rays). As a large fraction is absorbed or deflected by the atmosphere, lower levels of radiation occur at lower altitudes. In addition, charged particles such as protons interact with the magnetic field of the Earth and can be deflected or trapped by it (Rossi, 1970). This effect is reduced close to the magnetic poles, due to the orientation of the magnetic field lines. There, the field is no longer perpendicular to the trajectory of the incoming particles, but parallel. Charged particles are not affected by magnetic field lines parallel to their path though, and can therefore penetrate deeper into the atmosphere. Hence, increased cosmic radiation levels occur at high latitudes and personnel working in Antarctica (or the Arctic) will be subject to this radiation.

Most cosmic radiation comes in the form of high-energy protons (87%) or alpha particles (12%) (Gaisser, 1990). When encountering the atmosphere these can create an avalanche of high energy radiations, some of which are X-rays which have a greater range in the upper atmosphere and may reach the earth. The type of particles created largely depends on the energy of the incident particle. The sum of these created particles is called a cascade. This is illustrated in Figure 1.

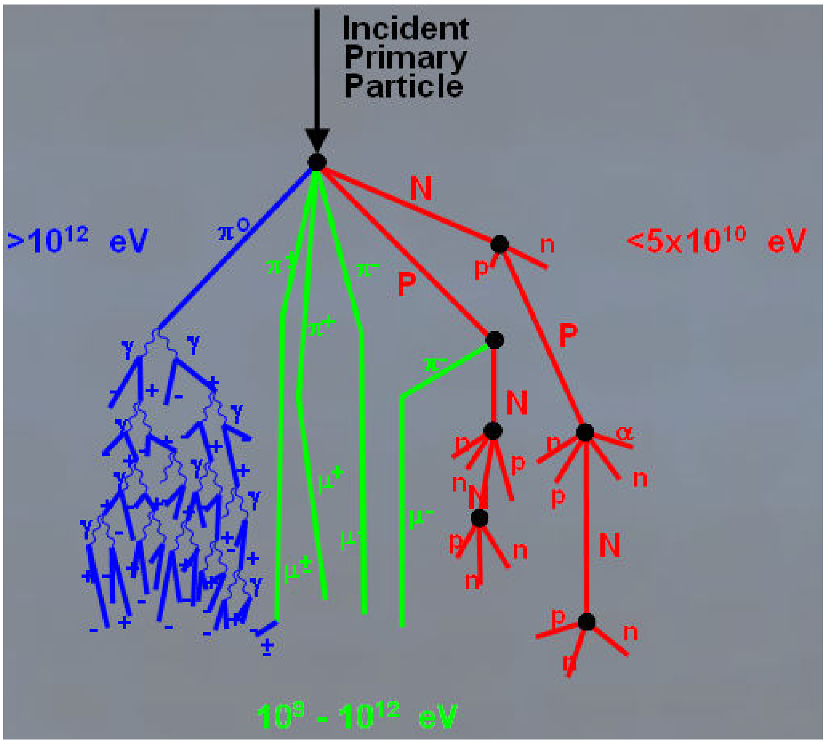

Figure 1: Cascades caused by cosmic rays in the atmosphere. Each incident primary particle creates a large number of different secondary particles, some of which are photons (γ's in the figure). A fraction of these has X-ray energies. (Source: Duldig, 2006)

These resulting particles are what mainly causes the dose received by humans due to cosmic background radiation. Of theses, neutrons can have the largest effect on the human body*[1], which is why numerous studies of neutron dosimetry in aircrafts have been conducted (e.g. Hewitt, 1978; Wilson, 1994).

Accordingly, this project was originally planned to include neutron, X-ray and UV measurements, using an appropriate detector. Unfortunately, the collaboration with an Australian University on this, did not work out. The prototype of a new dosimeter was supposed to be used for neutron measurements, but at the last minute, the Australians

[1] This is because they are heavier than most radiation and do not loose their energy via ionisation like protons, as they are uncharged. Their main effect is therefore due to collisions with protons. As they are of similar weight as protons, a collision knocks the proton out of its position. The proton can then do further damage to the tissue. As protons are extremely abundant in living organisms (e.g. in H_2O) neutrons have a strong effect on tissue.

decided they needed the prototype elsewhere during that period. Efforts to acquire a similar detector from Auckland failed as well. Hence, the study was limited to equipment available in the Physics & Astronomy Department of the University of Canterbury and the Medical Physics Department of the Christchurch Hospital.

Personnel dosimetry was conducted on 15 subjects who spent 2-5 weeks at various locations in Antarctica, using thermoluminiscent detectors (TLDs). The results were compared to the dose received by controls kept in Christchurch. The dosimeters were sensitive to high-energy X-rays, which can be produced in the aforementioned cascades.

While background radiation usually refers only to high energy ionizing radiation such as X-rays, non-ionizing UV radiation was also studied in this project, due to its known impacts on the skin and its other hazardous effects, e.g. on the human eye[2]. UV radiation is commonly divided into three types according to wavelength, but the precise definitions vary. We use the following classification (Skorucak, 2007):

- UVA: 400 nm – 320 nm
- UVB: 320 nm – 290 nm
- UVC: 290 nm – 100 nm

While the human skin has some inherent protection from UVA, UVB is most damaging. Increased levels of UVB can be expected in Antarctica due to the reduced levels of ozone in the atmosphere. Ozone is strongly absorbing at wavelengths between 200 nm and 300 nm (Wallace, 2006). Hence, less ozone leads to less absorption and higher levels of radiation at these wavelengths.

[2] The incidence of pterigium of the corneum is quite common in the South Island of New Zealand. This is associated with the increased levels of UV radiation in this area.

2. MATERIALS AND METHODS

2.1 X-RAY DOSIMETRY EQUIPMENT

Thermoluminescence detectors (TLDs) are solid state detectors with a special electronic structure that allow electrons to be trapped in energy levels higher than the ground state (valence band). A photon or electron can “knock” an electron from the (normal) valence band into a higher energy state in the conduction or exciton band, leaving a positive ‘hole’ in the valence band. Usually, the electron recombines after a short time with the hole and releases the gained energy again, as light. The material used in TLDs (LiF) is deliberately contaminated with imperfections (atoms that would not belong in a pure crystal). This creates special energetic states for electrons, which lie inside the “forbidden” energy region. Figure 2 illustrates this.

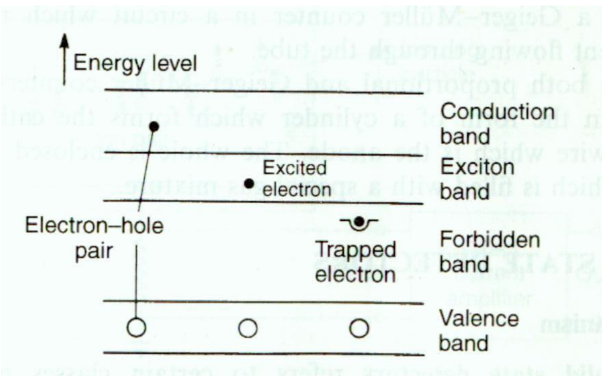

Figure 2: Energy levels and electron traps in TLDs. The number of electrons trapped is proportional to the amount of radiation exposure. (Source: Martin, 1999)

An electron can be excited into one of these states by cosmic radiation, either directly, or by “falling” into it from a state of higher excitation. It is then trapped and cannot recombine with a hole in the valence band. The number of trapped electrons is proportional to the amount of radiation the material was exposed to. When the material is heated to high temperatures, the trapped electrons can escape from the traps into the conduction band again due to their increased thermal energy. From here they can recombine with a hole, thereby releasing light. This luminescence can be detected with a photomultiplier tube and the total amount of light released (measured in nano-Coulomb (nC), the amount of charged collected in the photomultiplier tube) can be used to calculate the dose of cosmic radiation the detector was exposed to (Reich, 1990). After such a heating process, most of the electron traps are "empty" again and new measurements can be done. This is also called annealing and has to be done prior to any study with TLDs.

The term "dose" is very ambiguous in radiation dosimetry, as it has several meanings. Generally, it refers to the amount of Energy deposited in a medium per unit mass of the medium. Its unit is the Gray (1 Gy = 1 J/kg). This unit is usually used when talking about energy deposited by any kind of ionizing radiation. While this is a very sensible physical unit, it does not take into account that some types of radiation have much more detrimental effects on biological structures than others even if they are of the same energy. Particularly, neutrons and heavy nuclei can do much more damage than electrons or X-rays. Therefore, dose is often quoted in Sieverts (1 Sv = 1 J/kg), which is dose in Gray multiplied by a radiation weighting factor ω_R depending on the type of radiation considered. It ranges from 1 (for X-rays & electrons) to 20 (fast neutrons & heavy nuclei). Dose in Sv is called equivalent dose. As this study deals only with X-rays, $\omega_R = 1$ and dose (in Gy) and equivalent dose (in Sv) are essentially the same. Still both units will be used according to common practice.

In order to increase the probability of detecting the X-rays, the TLDs were surrounded by build-up caps. These were made out of a plastic that has a similar density to water ("tissue equivalent"). In this material, X-rays cause electrons to be released that have a much higher probability of depositing their energy in the dosimeters the incident medium to high energy X-rays. The caps were cylindrical, with a diameter of 25 mm. They were designed to maximize the sensitivity of the detectors to 1 – 50 MeV X-rays.

2.2 UV-MEASUREMENT EQUIPMENT

UV radiation was measured by using a Spectroline DRC-100X Digital radiometer with three sensors DIX254, DIX300 and DIX365, sensitive to UV light of 245nm (UVC), 300nm (UVB) and 365nm (UVA) wavelength respectively. The detailed relative response curves of these sensors are given in Figure 4 in Appendix 1.

Additionally, two UV-filters were used in combination with each of the sensors to limit the potential response of the sensors to visible light. The Corning 7-54 filter appears dark purple and the Corning 7-59 filter appears blue. They are referred to as F_a and F_b respectively. Their transmittance functions are given in Figure 5 and Figure 6 in Appendix 1.

3. APPLICATION AND RESULTING DATA

3.1 DISTRIBUTION AND READINGS OF TLD DOSIMETERS

The TLD dosimeters used for this study were annealed on 10th December 2006 at the Christchurch Hospital. They were then placed in pairs in small gelatine capsules and stored in a lead container until 21st December 2006.

A total of 19 build-up caps were filled with two TLD chips each. Four of these were placed on the windowsill of an office on the 8th floor of the Physics & Astronomy Department at the University of Canterbury, Christchurch, as a control group. The remaining 15 caps were dispersed among the GCAS-group*[3] of the author and several research groups going to Antarctica on the 21st December 2006. Most detectors returned to Christchurch with the author on 7th January 2007, after 16 days, while a few spent up to 42 days on the ice (see Appendix 2).

Additionally, ten TLDs were annealed and read out again to give a "zero-reading". The values for zero-dose are shown in Table 1. The average of 0.792 nC was subsequently subtracted from all other readings, as this part of the emitted light is not due to any radiation dose received.

Detector	Reading in nC	Detector	Reading in nC
Cal1	0.836	Cal6	0.858
Cal2	0.728	Cal7	0.864
Cal3	0.745	Cal8	0.764
Cal4	0.804	Cal9	0.769
Cal5	0.748	Cal10	0.803
Average	**0.792**		
SD	0.049		

Table 1: Measurements of the output of the TLDs without any radiation accumulation. SD is the standard deviation from the sample mean.

[3] Graduate Certificate of Antarctic Studies, a summer course at the University of Canterbury. This was the group the author went to Antarctica with.

In order to calibrate the measurements, ten further caps were irradiated at the hospital with 18MV*[4] X-rays. The detectors were placed at a distance of 4.24 m from the isocenter*[5]. A rectangular field of 2.6 cm x 11.7 cm was used. The equivalent square is such a field is 5 cm x 5 cm (=> correction factor 0.95 according to Kahn, 2003). Four dosimeters (again loaded with two TLDs each) were irradiated with 2 MU (monitor units), three with 5 MU and another three with 10 MU. Irradiation with 100 MU leads to a dose of 1 Gy at the isocenter. Hence, using the equivalent square correction and the inverse square law for amount of radiation at a distance from the isocenter, the respective doses administered to the dosimeters were:

$$\frac{2MU}{100\frac{MU}{Gy}} \cdot \frac{1}{(4.24)^2} \cdot 0.95 \approx 1.06mGy$$

$$\frac{5MU}{100\frac{MU}{Gy}} \cdot \frac{1}{(4.24)^2} \cdot 0.95 \approx 2.65mGy$$

$$\frac{10MU}{100\frac{MU}{Gy}} \cdot \frac{1}{(4.24)^2} \cdot 0.95 \approx 5.30mGy$$

Comparing these values with the readout form the TLDs gives a calibration factor that can be used to estimate the equivalent dose corresponding to the results from the Antarctic measurements. The calibration factor was 94±8 μSv/nC. For detailed calculations see Appendix 3.

[4] This is the acceleration potential used to create a spectrum of X-rays. The spectrum has a maximum X-ray energy of 18 MeV and peak intensity at approximately 6 MeV.

[5] The point in space to which a radiation source is calibrated.

3.2 Acquisition of UV-Data

UV-measurements in Antarctica were taken at different times of day and in different meteorological conditions and were compared with measurements under similar conditions in Christchurch. The high reflectivity of the snow and ice cover in Antarctica further increases the effective amount of UV any exposed skin or the human eye is subject to. To demonstrate this, measurements were also taken with different orientations of the detector. Detailed results are given in Appendix 4.

In order to approximate the combined effect of the wavelength-dependent properties of the filters and the sensors, the relative response functions were manually convolved with the transmittance curves. This was done by approximating the actual curves with their values at 5 nm intervals. The resulting “relative transmittance” functions for four of the possible combinations are given in Figure 3.

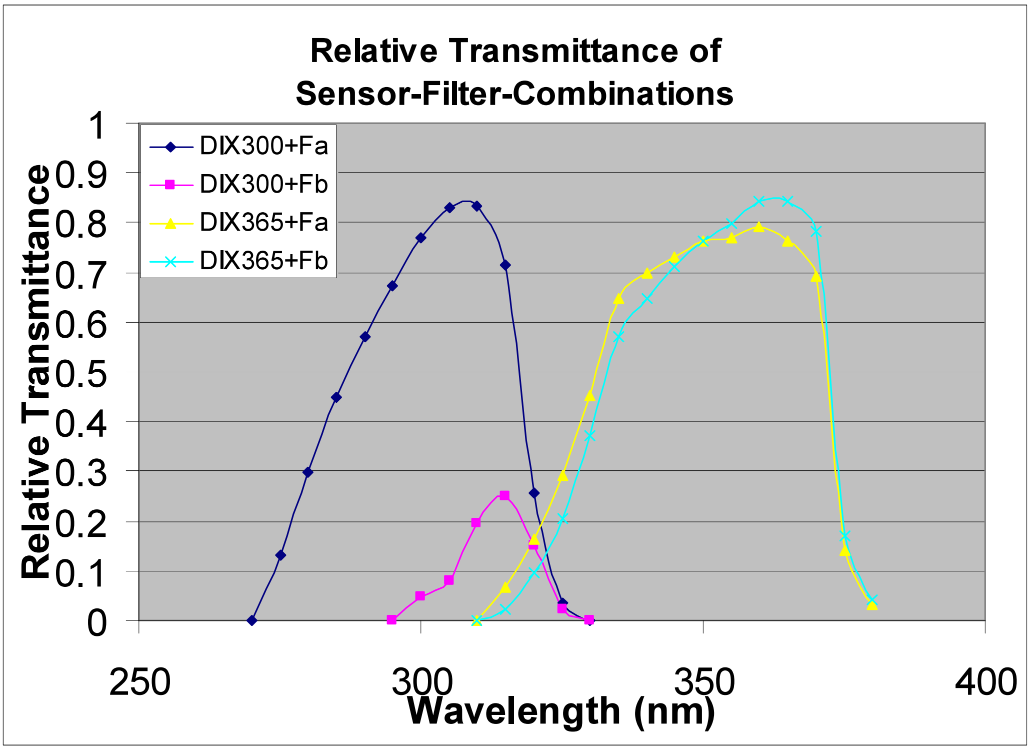

Figure 3: Approximate results of the convolution of the sensor response with the filter transmittance functions for the combinations of the DIX300 and DIX365 sensors with the F_a and F_b filters.

4. RESULTS AND DISCUSSION

4.1 PERSONNEL DOSIMETRY

Table 2 summarizes the results, which are given in more detail in Appendix 2.

Averages 1st Set (excluding T004,401&402)	Average Readout (nC)	Equivalent Dose from Calibration (mSv)	Sample-Error (SD from mean) (nC)	Sample Error in %	Ratio Anta/Chch
Christchurch	1.852	**0.174**	0.106	**6%**	
Antarctica	2.127	**0.200**	0.651	**31%**	**1.15**

Table 2: Summary of results of TLD dosimetry. An increase in radiation levels by 15% was detected, but is not significant, as the standard deviation (of the Antarctic measurements) from the sample mean is very high (31%).

The calibration factor calculated earlier is used to estimate the equivalent total dose. The values of 0.174 mSv in Christchurch and 0.2 mSv in Antarctica (during a period of 46 days) are very high. The global average equivalent dose due to cosmic radiation is 0.3 mSv per year. Hence, the calculated equivalent doses are most likely much higher than actually received values, which is probably due to wrong assumptions in the calibration calculations (e.g. administered dose in Gy is assumed to be equal to the absorbed equivalent dose in Sv). Still, the results are at least of the expected order of magnitude. This indicates that absolute values of equivalent dose could be achieved with improved calibration methods in prospective studies.

Anyhow, the results are encouraging. All measurements are significantly higher then the zero-readings and lie beyond even 3 SDs of these. Hence, our results are not just "noise" but actual dosimetric measurements. Consistence of the data is also seen in when comparing the three control caps (T001-T003) that were read out on 24th January with the results from the last control cap (T004). The reading from the last capsule is about 30% higher than the readings from the first three, which is in accordance with the amount of extra days of exposure of T004 (within the SD of the results).

Some of the data seems to show a trend of higher readings according to time spent at higher magnetic latitudes. E.g. T301 was mainly at McMurdo Station but took a four day trip to the South Pole (which is at about 6° lower magnetic latitude than McMurdo). It reads slightly lower than T303, which spent the whole time at McMurdo. Similarly, T302 spent 20 days at the South Pole and 2 days at McMurdo and shows a reading similar to the average of T101-T104, which spent less time in Antarctica (only 16 days total) but at higher magnetic latitude (Windless Bight, Ross Island). Unfortunately, there are also some major deviations that cannot be explained in this way.

The spread of the results even at identical locations is significant and a matter of concern. The most prominent example are T201 and T202. These caps were kept in the same place right, next to each other, all throughout their stay in Antarctica, but one shows a 40% higher reading than the other. This cannot be explained by differences in sensitivity of the TLDs, as these would only be of the order of 5%. The results of T401 and T402 are similarly puzzling. While these were carried by two individuals, both spent the entire time at the same locations. Furthermore, they spent a significant amount of time at altitudes above 2500 m and even approximately 50 hours in an airplane at 4200 m altitude. Although this was at locations of lower magnetic latitude than Scott Base or McMurdo Station, the increased radiation at higher altitudes could be expected to outweigh the effect of lower latitude and lead to higher readings. This is only observed in one of the two caps and therefore a systematic increase cannot be concluded.

While the average of the measurements in Antarctica is slightly higher than the Christchurch control readings (15% increase), this difference is not significant, due to the high variability of the results (31% SD). The difference of 0.275 nC lies within the 0.651 nC standard deviation (SD) of the measurements. Considering values from aircrew dosimetry, the expected increase in cosmic radiation at ground level from low to high latitudes is approximately 10 percent (NRL, 1998). At flight altitudes of 12 km, this effect is assumed to be much more pronounced and a two fold increase in radiation has been measured (NRL, 1998). Unfortunately, the variability of our results is much higher than the expected 10 percent difference. This is due to the equipment used. TLD dosimeters are commonly employed for measurements of much higher doses than the ones received in this study. While a SD of 0.651 nC would not be very large for readouts of several tens or hundreds of nC (e.g. the calibration readings), it strongly impacts the significance of our dosimetric measurements. The dosimeters used were not accurate enough to give reliable results, and better (more expensive) equipment would have been required.

4.2 UV LEVELS

Measurements with the DIX254 sensor were discarded (David Goode, private communication). Goode indicated that he would not expect any measurable UVC levels in Christchurch or Antarctica and suggested that the readings using the DIX254 are due to absorption of much longer wavelengths. Through his experience he noted that the sensors are not as insensitive to long wavelength radiation as the manufacturer claims. Therefore, measurements without filters are also neglected. While the filters also transmit some infrared (see Appendix 1), the transmittance of the filters at long wavelengths is at least tabulated. It seems to be the smallest in the case of the 7-54 (F_a) filter. Hence, measurements with this filter are least affected by longer wavelength radiation.

As the transmittance of the F_a filter is relatively high for both UVA and UVB radiation (see also blue and yellow curve in Figure 3), the following discussion focuses on the readings with this filter. The detailed UV measurements are given in Appendix 4. Table 3 shows a sample of the measurements using the F_a filter.

Conditions	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy
Time of Day	14:00	15:00	15:45	16:00	17:00	18:30
Antarctica						
DIX300+F_a	90	160	80		30	70
DIX365+F_a	880	850	1050		630	680
Christchurch						
DIX300+F_a				0		
DIX365+F_a				20		

Conditions	Clear	Clear	Clear	Clear
Time of Day	12:00	14:00	17:30	21:00
Antarctica				
DIX300+F_a	270			150
DIX365+F_a	2760			1170
Christchurch				
DIX300+F_a		120	110	
DIX365+F_a		1480	400	

Table 3: Extract of the UV-measurements acquired. Irradiance is given in μW/cm^2. The full data set is given in Appendix 4.

These figures show a general increase in UVA and UVB levels in Antarctica compared to Christchurch. This means a decreased opacity of the atmosphere to UV light, potentially due to the depleted ozone layer over Antarctica. This effect is larger than the increased effective atmospheric thickness due to the higher zenith angle of the Sun in Antarctica. Particularly, the UVB levels at noon on a clear day are doubled. Due to the 24-hour sunlight, the UVB levels are constantly high on clear days in Antarctica and even UVB measurements under partly cloudy conditions or at 9:00 p.m. were higher than at noon in Christchurch. This clearly shows that increased protection from the Sun is necessary and it is with good reason that using factor 30 sunscreen even at nighttime is common practice in Antarctica.

Although a relative increase in UV radiation can be derived from our data, conclusions about the absolute power per unit area cannot be drawn with any certainty. While the readings of the radiometer are in μW/cm^2, it was last calibrated in 1991 and since then the accuracy could have reduced by more than 20%. Also, the response curves of the sensors given in Appendix 1 are in relative units. Therefore, the actual power of the incoming UV light is likely to be higher than the measured value and the absolute sensitivity cannot be derived. Finally, in contrast to the manufacturer's claim, experience has shown that the sensors do respond to infrared radiation, which artificially increases the readings even further. However, it is worth noting that the total relative transmittance of the sensor/filter system is approximately 50% when using the F_a filter with the DIX300 and DIX365*[6]. This means that doubling the readings could give an estimate of the actual irradiance at these wavelengths. In terms of our UVA readings, this amounts to ≈ 3mW/cm^2 at 2 p.m. on clear day in Christchurch and ≈ 5.5mW/cm^2 at 12 noon in Antarctica. While these values are probably not very accurate, they are of the expected order of magnitude (Balasaraswathy, 2002).

The readings at different orientations (see Appendix 4) of the sensors show two important aspects that have to be kept in mind in Antarctica. As 99% of the continent is covered by snow and ice, reflection of UV radiation from the ground is much more important than on ice-free ground. Readings of the reflected radiation (sensor facing the ground) are up to 20 times higher in Antarctica. This is further emphasized by measurements under overcast conditions. In this case, UV levels measured in Antarctica were very similar for upward and horizontal orientation of the sensors and generally much higher than under similar conditions in Christchurch.

[6] The blue and the yellow curve in Figure 3 cover about half of the area of the full rectangle in the sensitive range of wavelengths.

5. CONCLUSION AND OUTLOOK

The initial motivation of this project was that numerous theoretical explanations for an only minor increase of cosmic radiation in polar regions exist, but the author was unable to find a single study that had attempted to prove this. While our results are not sufficiently accurate to count as absolute measures of cosmic radiation levels, they do allow the statement that radiation levels are probably of a similar order in Antarctica and not much higher or lower. At the least, this has to be true for X-rays of the considered energies. For a small, preliminary study such as this one, that is a satisfactory outcome.

As the impacts of low levels of radiation remain uncertain and epidemiologic studies, trying to assess the effects of increased levels of background exposure, continue to struggle with getting significant results (Boice et al., 2000), cosmic ray dosimetry continues to be a field open to further investigation. While there have been numerous cosmic ray surveys (e.g. Dorman et al., 2000) the radiation protection aspect is rarely considered. Hence, further data acquisition and study of Antarctic radiation levels seems desirable.

A future project should make use of more suitable equipment such as a modern, calibrated UV-radiometer and include neutron dosimetry. Of course, this requires a significantly higher amount of funding and preparation than for this preliminary study and is probably not suitable as a GCAS personal project, due to the required amount of time. Still, the subject remains a field of current interest and is likely to find more attention in the near future. Already, there are ongoing preparations for a much larger project on the other side of the globe. In a personal email a German employee indicated to the author that the GSF-Institute, is planning a three-year study in Spitsbergen, employing sophisticated neutron-spectrometry equipment, known as Bonner Spheres in order to determine detailed neutron spectra.

Furthermore, it has been suggested that skin exposed to high levels of UV is more sensitive to damage by other types of radiation such as cosmic rays. This is not very well studied so far, but the combination of increased UV and cosmic ray levels in Antarctica could be used to do so.

6. ACKNOWLEDGEMENTS

Firstly, I want to thank my supervisor Dr. John Turner for all his support, advice and for giving me the opportunity to conduct this survey.

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Great thanks go to Charles Kaminski, Jay Kyne, Dr. Kathy Licht and Dr. James Madsen from the US Antarctic Program for their help with this project by wearing the TLD dosimeters throughout their operations in Antarctica. This spread over the continent was essential to giving the project validity, as otherwise only measurements on Ross Island would have been possible and the outcome could have easily been mistaken as a local anomaly and discarded.

Finally, I want to express my gratitude to Professor Bryan Storey and Gateway Antarctica for making the whole project possible through the Graduate Certificate of Antarctic Studies course.

Once again thank you all.

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APPENDICES

APPENDIX 1: UV-FILTER AND SENSOR RESPONSE CURVES

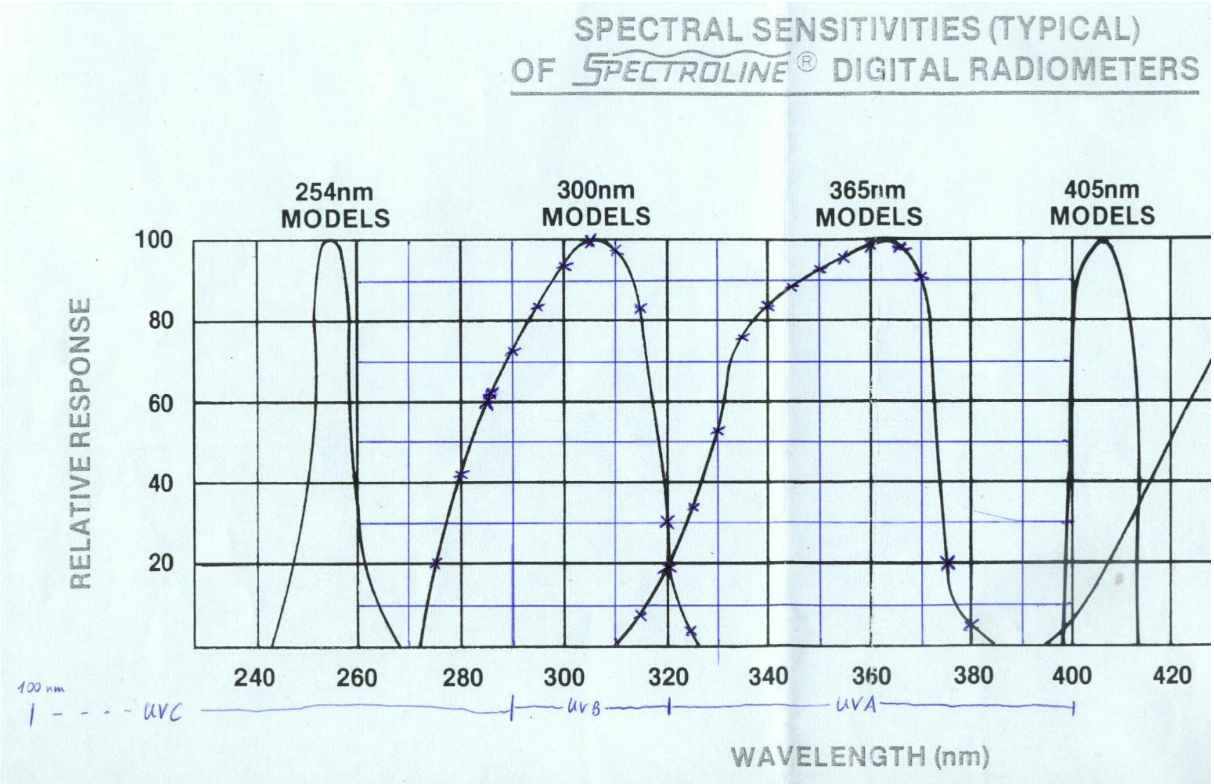

Figure 4: Relative response curves of the DIX filters.

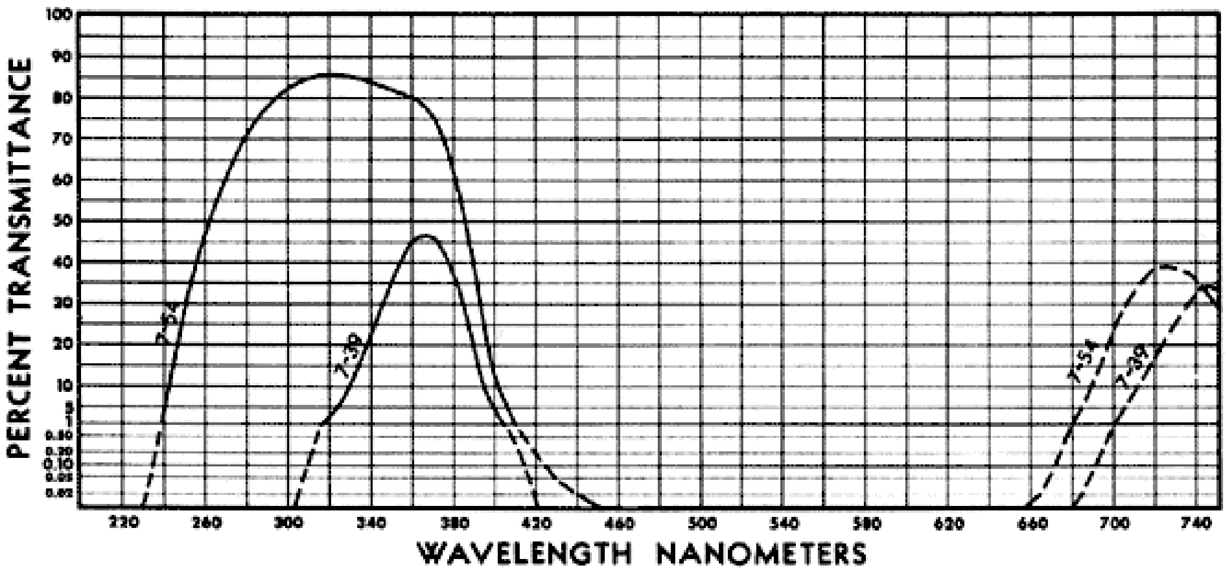

Figure 5: Transmittance of “black” UV-filter (referred to as F_a), Corning 7-54.

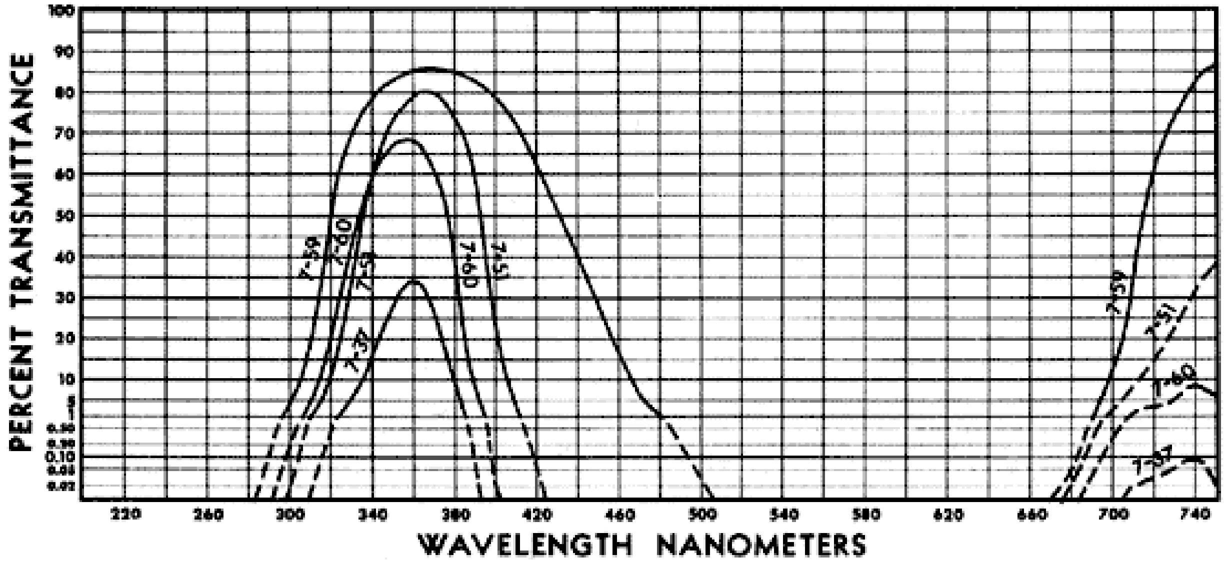

Figure 6: Transmittance of “purple” UV-filter (referred to as F_b), Corning 7-59.

APPENDIX 2: TLD READINGS

Detector	Read-out date	Read out (nC)	"Zeroed" (nC)	Capsule Averages (nC)	Location	time in Antarctica @ Ross Island (d)
T001	24/01/2007	2.526	1.734	1.760	CHCH / Physics 8th floor	0
T001	24/01/2007	2.578	1.786		CHCH / Physics 8th floor	0
T002	24/01/2007	2.751	1.959	1.965	CHCH / Physics 8th floor	0
T002	24/01/2007	2.763	1.971		CHCH / Physics 8th floor	0
T003	24/01/2007	2.548	1.756	1.830	CHCH / Physics 8th floor	0
T003	24/01/2007	2.696	1.904		CHCH / Physics 8th floor	0
T004	5/02/2007	3.45	2.658	2.505	CHCH / Physics 8th floor	0
T004	5/02/2007	3.143	2.351		CHCH / Physics 8th floor	0
T101	24/01/2007	2.279	1.487	1.644	N/GCAS	16
T101	24/01/2007	2.593	1.801		N/GCAS	16
T102	24/01/2007	3.560	2.768	3.540	M/GCAS	16
T102	24/01/2007	5.103	4.311		M/GCAS	16
T103	24/01/2007	3.029	2.237	2.014	S/GCAS	16
T103	24/01/2007	2.582	1.790		S/GCAS	16
T104	24/01/2007	3.365	2.573	2.300	D/GCAS	16
T104	24/01/2007	2.818	2.026		D/GCAS	16
T201	24/01/2007	4.389	3.597	3.074	West Anarctic	2+
T201	24/01/2007	3.342	2.550		Ice Sheet Divide	2+
T202	24/01/2007	2.468	1.676	1.909	West Anarctic	2+
T202	24/01/2007	2.933	2.141		Ice Sheet Divide	2+
T203	24/01/2007	2.533	1.741	1.717	GCAS - Café Bavaria	16
T203	24/01/2007	2.484	1.692		GCAS - Café Bavaria	16
T204	24/01/2007	2.824	2.032	1.885	Scott Base (inside)	16
T204	24/01/2007	2.530	1.738		Scott Base (inside)	16
T301	24/01/2007	2.351	1.559	1.517	South Pole + McMurdo	12
T301	24/01/2007	2.266	1.474		South Pole + McMurdo	12
T302	24/01/2007	3.267	2.475	2.405	South Pole	2
T302	24/01/2007	3.127	2.335		South Pole	2
T303	24/01/2007	2.578	1.786	1.745	McMurdo	16
T303	24/01/2007	2.495	1.703		McMurdo	16
T401	5/02/2007	2.425	1.633	1.753	close to Beardmore Glacier	22
T401	5/02/2007	2.665	1.873		+ Twin Otter + McMurdo	22
T402	5/02/2007	3.53	2.738	2.786	close to Beardmore Glacier	22
T402	5/02/2007	3.626	2.834		+ Twin Otter + McMurdo	22
T501	24/01/2007	2.470	1.678	1.885	GCAS - Tent Top	16
T501	24/01/2007	2.884	2.092		GCAS - Tent Top	16
T502	24/01/2007	2.611	1.819	2.025	Scott Base (outside)	16
T502	24/01/2007	3.023	2.231		Scott Base (outside)	16

Detector	time in Antarctica not @ Ross Island (d)	total exposure time (d)	lat. (°S)	magn. lat. (°S)	altitude (m)
T001	0	46	43.5	50.24	40
T001	0	46	43.5	50.24	40
T002	0	46	43.5	50.24	40
T002	0	46	43.5	50.24	40
T003	0	46	43.5	50.24	40
T003	0	46	43.5	50.24	40
T004	0	58	43.5	50.24	40
T004	0	58	43.5	50.24	40
T101	0	46	77.8	79.97	20
T101	0	46	77.8	79.97	20
T102	0	46	77.8	79.97	20
T102	0	46	77.8	79.97	20
T103	0	46	77.8	79.97	20
T103	0	46	77.8	79.97	20
T104	0	46	77.8	79.97	20
T104	0	46	77.8	79.97	20
T201	20-	46	79.47	66.96	1759
T201	20-	46	79.47	66.96	1759
T202	20-	46	79.47	66.96	1759
T202	20-	46	79.47	66.96	1759
T203	0	46	77.8	79.97	20
T203	0	46	77.8	79.97	20
T204	0	46	77.8	79.97	10
T204	0	46	77.8	79.97	10
T301	4	46	90 & 77.8	74.06 & 79.97	2835 & 10
T301	4	46	90 & 77.8	74.06 & 79.97	2835 & 10
T302	20	46	90.0	74.06	2835
T302	20	46	90.0	74.06	2835
T303	0	46	77.8	79.97	10
T303	0	46	77.8	79.97	10
T401	20	58	77.8 & 85-87.5	79.97 & 77.70 - 73.16	10 & 2500 & 4200
T401	20	58	77.8 & 85-87.5	79.97 & 77.70 - 73.16	10 & 2500 & 4200
T402	20	58	77.8 & 85-87.5	79.97 & 77.70 - 73.16	10 & 2500 & 4200
T402	20	58	77.8 & 85-87.5	79.97 & 77.70 - 73.16	10 & 2500 & 4200
T501	0	46	77.8	79.97	20
T501	0	46	77.8	79.97	20
T502	0	46	77.8	79.97	10
T502	0	46	77.8	79.97	10

Summaries

Calibration factor:	**94±8**	µSv/nC				
Averages 1st Set	Average readout	Dose from		sample-error	sample error	Anta/Chch
(excluding T004,401&402)		Calibration		(SD from mean)	(in %)	
	(nC)	(mSv)		(nC)		
Christchurch	**1.852**	0.174		0.106	**6%**	
Antarctica (all)	**2.127**	0.200		0.651	**31%**	**1.15**
GCAS (only individuals)	2.374	0.223		0.890	37%	1.28
GCAS (whole camp)	2.183	0.205		0.771	35%	1.18
CGAS (incl. Scott Base)	2.126	0.200		0.675	32%	1.15
only non-GCAS	2.130	0.200		0.646	30%	1.15
Averages 2nd Set						
Christchurch	2.505	0.235		0.217		
Beardmore&McMurdo	2.270	0.213		0.606		0.91

APPENDIX 3: TLD CALIBRATION

Dose Administered (MU)	Reading in nC	"zero" subtracted (nC)	Average (nC)	Error SD from mean	Dose given (mGy)	Calibration Factor (mGy/nC)	Calibration Error (mGy/nC)
2	11.973	11.181	11.041	0.704377	1.06	0.096	0.0061
2	10.731	9.939					
2	12.146	11.354					
2	11.610	10.818					
2	11.761	10.969					
2	12.686	11.894					
2	11.054	10.262					
2	12.700	11.908					
5	29.937	29.145	28.591	0.89589	2.65	0.093	0.0029
5	29.957	29.165					
5	30.164	29.372					
5	27.734	26.942					
5	29.171	28.379					
5	29.332	28.540					
10	54.115	53.323	56.353	2.312669	5.30	0.094	0.0039
10	57.369	56.577					
10	58.924	58.132					
10	59.436	58.644					
10	54.476	53.684					
10	58.550	57.758					
				Average Calibration		**0.094**	
				Error (sum of squares)			0.0078

"Zero Readings"

Detector	Reading in nC	Detector	Reading in nC
Cal1	0.836	Cal6	0.858
Cal2	0.728	Cal7	0.864
Cal3	0.745	Cal8	0.764
Cal4	0.804	Cal9	0.769
Cal5	0.748	Cal10	0.803
Average	**0.792**		
SD	0.048642574		

APPENDIX 4: UV-READINGS

Radiometric measurements

							GPS coord:	Windless B	E77.46"70.7"			Castle Rk	E77.48'49"		Hutton Cl	E77.43'42"	
Spectroline DRC 100× digital radiometer			the radiometer measures irradiance in µW/cm^2						S166.57'22.2"				S166.46'28.1"			S166.51'17.5"	
was used with 2 different sensors:																	
	DIX #300, #365																
2 filters:	Fa - dark purple	**Corning 7-54**															
	Fb - blue	**Corning 7-59**															
			O R I E N T A T I O N S														
			upwards					**horizontal**					**downwards**				
		sensor	**no filter**	**with Fa**	**with Fb**	**s'glasses**	**goggles**	**no filter**	**with Fa**	**with Fb**	**s'glasses**	**goggles**	**no filter**	**with Fa**	**with Fb**	**s'glasses**	**goggles**
Date	18-Dec-06																
Location	Uni of canterbury																
	lawn outside law bldg	**#300**	550	110	270	40	90	490	60	60	20	20	90	10	30	10	10
Cloud Cover	clear	**#365**	620	400	540	0	10	450	140	180	0	10	200	10	10	0	0
Time	1730									120					0		
Date	25-Dec-06																
Location	Windless Bight																
	GCAS campsite	**#300**	120	90	60			120	30	40			100	90	90		
Cloud Cover	overcast	**#365**	1150	880	1050			1150	900	1180			950	690	790		
Time	1400																
Date	26-Dec-06																
Location	Windless Bight																
	GCAS campsite	**#300**	100	70	60			100	60	60			90	70	70		
Cloud Cover	overcast	**#365**	980	680	800			980	700	860			820	510	680		
Time	1830																
Date	27-Dec-06																
Location	Castle Rock																
	300m above sea level	**#300**	100	160	70			130	300	80			70	130	60		
Cloud Cover	overcast	**#365**	1160	850	1030			1220	890	1070			800	540	660		
Time	1500																
								away / towrds sun	**away / towrds sun**	**away / towrds sun**				**over ice / over snow**			
Date	28-Dec-06																
Location	Hutton Cliffs																
	on sea-ice	**#300**	410	270	300			210/330	160/170	80/230			150	170/260	210		
Cloud Cover	clear	**#365**	2680	2760	2320			990/2170	940/1740	880/1820			640	640/730	680		
Time	1200																

			O R I E N T A T I O N S														
			upwards					**horizontal**					**downwards**				
								away / towrds sun	**away / towrds sun**	**away / towrds sun**							
Date	30-Dec-06																
Location	Windless Bight																
	GCAS campsite	**#300**	190	190	80	10	60	60/280	30/130	20/100	20	30	70	70	60	20	30
Cloud Cover	partly cloudy	**#365**	1180	990	1090	10	10	440/1250	370/990	420/840	10	10	670	340	520	10	20
Time	1830																
								away / towrds sun	**away / towrds sun**	**away / towrds sun**							
Date	31-Dec-06																
Location	Windless Bight																
	GCAS campsite	**#300**	350	150	240	30	70	50/300	30/150	30/230	10	30	70	50	60	20	50
Cloud Cover	clear	**#365**	1530	1170	1300	10	20	680/1340	510/1000	570/1140	10	10	550	420	460	10	20
Time	2100																
			away / towrds sun	**away / towrds sun**	**away / towrds sun**												
Date	1-Jan-07																
Location	Windless Bight																
	GCAS campsite	**#300**	140/160	70/80	90/80	30	70	120	70	90	20	60	110	70	90	10	60
Cloud Cover	overcast& snowing	**#365**	1240/1430	930/1050	1040/1100	20	30	1300	940	1020	10	10	900	660	680	0	10
Time	1545																
			away / towrds sun	**away / towrds sun**													
Date	5-Jan-07																
Location	Scott Base																
	outside front bldg	**#300**	50/70	20/30	30	0	0	30	20	30	0	10	10	0	0	0	0
Cloud Cover	overcast	**#365**	710/800	580/630	630	0	10	490	270	380	10	20	50	0	30	0	0
Time	1700																
								away / towrds sun									
Date	2-Feb-07																
Location	Uni of canterbury																
	lawn outside law bldg	**#300**	350	120	180	60	190	40/180	30	50	30	10	60	10	30	10	0
Cloud Cover	clear	**#365**	1920	1480	1600	0	0	120/610	400	420	10	0	10	10	20	0	0
Time	1400																
Date	5-Feb-07																
Location	Uni of canterbury																
	lawn outside law bldg	**#300**	40	0	10	0	0	30	0	10	0	0	0	0	0	0	0
Cloud Cover	5/8 overcast	**#365**	260	20	10	0	10	90	10	60	0	0	40	0	20	0	10
Time	1600																